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Cover Page Footnote

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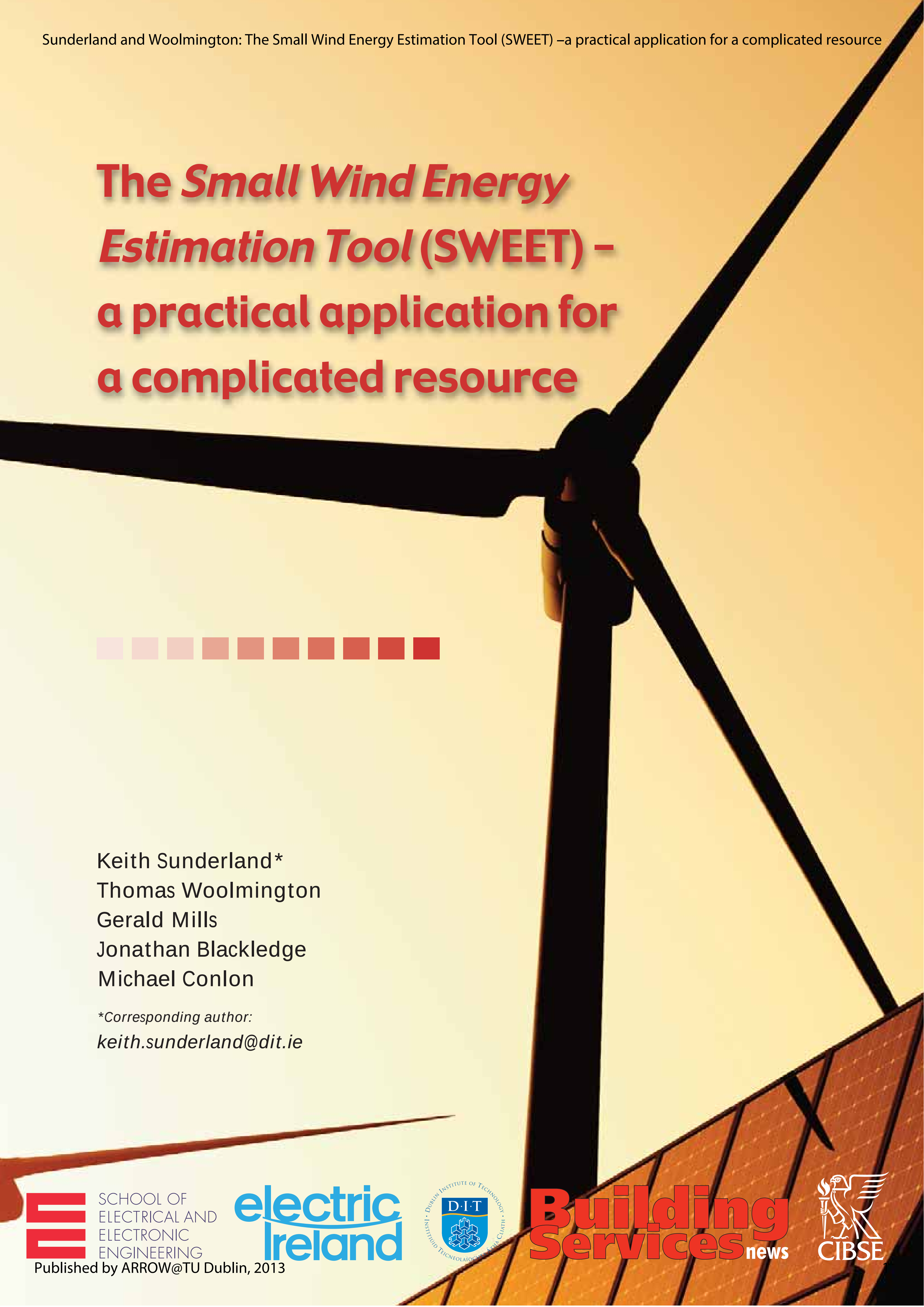

The *Small Wind Energy Estimation Tool* (SWEET) – a practical application for a complicated resource

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Abstract

Of the forms of renewable energy available, wind energy is at the forefront of the European (and Irish) *green* initiative with wind farms supplying a significant proportion of electrical energy demand. Increasingly, this type of distributed generation (DG) represents a "paradigm shift" towards increased decentralisation of energy supply. However, because of the distances of most DG from urban areas where demand is greatest, there is a loss of efficiency. One possible solution, placing smaller wind energy systems in urban areas, faces significant challenges. However, if a renewable solution to increasing energy demand is to be achieved, energy conversion systems in cities, where populations are concentrated, must be considered.

That said, assessing the feasibility of small/micro wind energy systems within the built environment is still a major challenge. These systems are aerodynamically rough and heterogeneous surfaces create complex flows that disrupt the steady-state conditions ideal for the operation of small wind turbines. In particular, a considerable amount of uncertainty is attributable to the lack of understanding concerning how turbulence within urban environments affects turbine productivity. This paper addresses some of these issues by providing an improved understanding of the complexities associated with wind energy prediction.

This research used detailed wind observations to model its turbulence characteristics. The data was obtained using a sonic anemometer that measures wind speed along three orthogonal axes to resolve the wind vector at a temporal resolution of 10Hz. That modelling emphasises the need for practical solutions by optimising standard meteorological observations of mean speeds, and associated standard deviations, to facilitate an improved appreciation of turbulence. The results of the modelling research are incorporated into a practical tool developed in EXCEL, namely the *Small Wind Energy Estimation Tool* (SWEET). This tool is designed to assist engineers gain an intuitive appreciation of the limitations associated with this form of energy. It is only through an understanding of such limitations that informed decisions can be made which ultimately facilitate more intelligent installations

Key Words:
Small wind turbines, urban environments, turbulence, turbulence intensity, Gaussian and Rayleigh distributions.

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1. Introduction

To produce electrical energy, wind turbines extract kinetic energy from moving air and convert it into mechanical energy, from which the turbine rotor derives electricity through the generator. Micro wind turbines can be either horizontal axis (HAWT) or vertical axis (VAWT) and are distinguished by blade diameter, cut-in/rated wind speed, and output power at rated wind speed. The two defining aspects of a wind turbine's performance are the blade sweep area and the associated power curve for the turbine. The blade sweep area defines the amount of power that can be captured from the available wind while the power curve describes the turbine's performance against varying wind speeds. The mechanical energy captured by the wind rotor is defined by the Betz constant in the equation describing mechanical power through wind energy:

$$P_{Mech} = \frac{1}{2} \cdot C_p \cdot P_{air} \cdot A_{rotor} \cdot u^3 \quad (1)$$

where

– C_p, is the power coefficient, defining how much wind power is captured and turned into mechanical power to subsequently generate electricity

– ρ_{air}, is the mass density of air;

– A_{rotor}, is the rotor area ($\pi.R^2$ where R is the length of the blades);

– u is the wind speed.

According to the *Betz* limit, the maximum possible conversion coefficient for any laminar kinetic process is 59.3%. However, there are underlying assumptions in this calculation that all the energy conversion is kinetic in nature and that the mass flow is non-turbulent. This Betz limit does not strictly hold true for a turbulent wind resource, which reduces the overall power-producing capability for a given technology. Also, as turbulence is very much site-specific, a viable metric needs to be used in order to quantify its intensity and its likely effects on a given turbine technology.

In practice, losses due to (aerofoil) blade roughness, wake effects, hub loss and tip losses reduce the coefficient of performance to much lower values and, as such, typical values range from 0.1-0.35 for the majority of commercially-available small/micro turbines. If the wind is unsteady the energy conversion capability of the turbine is further degraded.

Eqn (1) suggests that, in an ideal scenario, the power generated is proportional to the cube of wind speed (u^3) but, for a number of reasons, this does not hold true for the majority of turbines. Firstly, the drag on most turbines is relatively static when compared to the wind speed at the height of the generator (hub-height); some of the newer techniques do use technologies such as furling of the blades or blade pitch control but these only respond within the operational range of the turbine, e.g. 3-15m/s. Secondly, the vast majority of grid-interfaced inverters function in a linear manner so that doubling the wind speed produces double the power. A block diagram description of how micro wind generation technologies connect in parallel with the distribution network (in Ireland) is illustrated in Figure 1, contextualised with the flow of power conversion associated with these technologies.

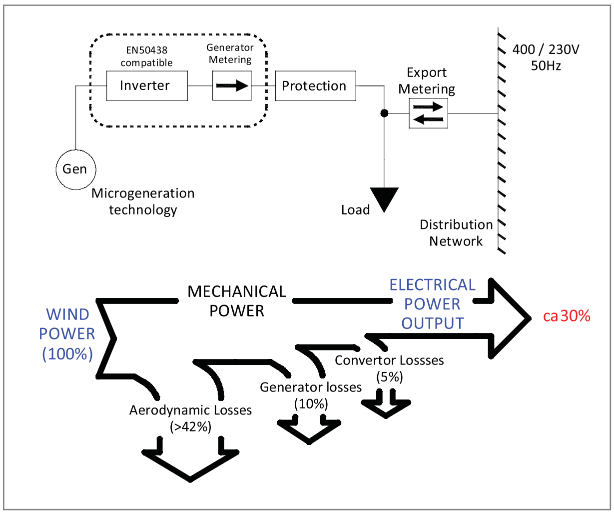

Figure 1: Block diagram of grid-tie logistics for small/micro wind systems contextualised in terms of the typical flow of power conversion

While the micro wind sector is still at an early stage of development, there is evidence of a growing market for micro wind systems[1]. From an Irish perspective, microgeneration technologies are identified in legislation as options for alternative energy supply. For example, the recently-published *Building Regulations (Part L Amendment)*[2] stipulate that for new installations, "a reasonable proportion of the energy consumption to meet the energy performance of a dwelling is provided by renewable energy sources".

In reality, micro-generation uptake in Ireland has been relatively poor, even though there is a technical and fiscal infrastructure in place. At the end of 2011 there was nearly 3MW of micro generation grid connected, representing an increase of 49.8% capacity compared to 2010 (1962.73kW[3]). While there is long way to go before the sector can make an impact on renewable energy targets, it is still the most embraced microgeneration technology of choice in Ireland with 79.2% of the 620 connections. The wind turbines considered in these statistics have installed capacities ranging from 500W up to 17kW, although under the micro generation connection[4] criteria, only technologies with ratings up to 6kW are considered as micro generation.

The Irish Distribution Network Operator (DNO) ESB Networks – and the Commission for Energy Regulation (CER) – have a conservative attitude towards microgeneration in general. The UK, on the other hand, has a strong commitment to the embracement of power generation from small wind energy systems with 160.96 MW capacity across the sector[1]. Indeed, the UK Government has ambitious targets and aspires to have 2% of national electricity demand supplied from small scale source[5]. While wind power at micro level in the UK currently represents only 0.35% of total wind capacity[6], with potential for micro generation as high as 30-40 % of the UK's electricity needs[7], micro wind generation capacity is expected to increase significantly.

From an urban wind energy perspective, most research on the energy potential of such systems is somewhat biased. The performance of wind turbines tends to be assessed in ideal circumstances[8, 9]. In the urban environment, the initial cost of micro wind turbines and the locations in which units are likely to be installed (i.e. where the wind speed and direction are very dependent on the site, proximity to potential obstacles etc) have received little attention. So, the energy yield of the turbine rather than the available wind resource is studied. As a consequence, inappropriate locations for installation can never realise the energy potential.

There is therefore a deficiency in our understanding of the potential energy that could be harnessed from micro wind energy systems as well as the viability of these systems to provide a cost-effective power generation option[10]. Missing from most of the aforementioned research is the technology's primary energy source, the wind. There is significant research assessing the wind energy resource in "rural" locations around the world[11-13], and in some research[14, 15] such work has been extended to apply to the potential for wind energy conversion systems. However, the available test studies that investigate the viability of micro wind generation in urban centres are more generic and broader, suggesting that the technology can work if installed correctly and in appropriate locations[8, 9].

An improved understanding of the wind resource, therefore, could potentially lead to improved choices of installation locations and more realistic productivity expectations from this form of energy system. As global populations increasingly migrate towards urban centres, small wind energy systems, either for urban dwellings or for green-field locations, must be considered as a contribution option towards renewable energy targets[16].

2. The urban wind resource and wind energy systems

General adjectives that describe the wind resource include variability and unpredictability. Indeed, a full understanding of the resource is further complicated due to the fact that these characteristics are geographically and temporarily interdependent. As Burton describes[17], the variability of the wind preserves over an extensive range of scales, both in space and time. This property is enhanced in built environments where airflow is highly disturbed. Wind turbines are most efficient when airflow is strong and steady, that is high mean wind speeds with little variability in speed or direction.

Urban areas disturb the airflow (reducing the mean wind speed and increasing variability) and produce sub-optimal environments for turbines. However, little is known of the actual wind resource in urban areas and a major (technical) barrier to the effective deployment of wind turbines in these areas is due to a lack of accurate methods for estimating wind speeds and energy yields at potential urban sites[18]. This is because cities are aerodynamically rough and heterogeneous and have a highly-localised and complex wind environment.

Air flowing across an urban area will interact with the underlying surface and become affected by its roughness characteristics. The result is the formation of a distinctive boundary layer that grows in depth from the upwind edge of that surface type. Where the air flows across a series of surfaces, each of a different roughness, a series of Internal Boundary Layers (IBL) form in the along-wind direction. The growth of the IBL depends on the intensity of turbulence that transmits the effects of roughness upwards and this depends on wind-speed, surface roughness and atmospheric stability[19]. The latter describes the relative tendency for an air parcel to move vertically as a result of buoyancy and is regulated by the thermal structure[19]. Whereas unstable conditions promote vertical mixing, stable conditions suppress it. However, the Irish climate is dominated by neutral conditions, so that wind-speed and surface roughness are the main factors regulating turbulence intensity[20].

Over extensive homogenous surfaces, the wind-speed (u(z)) at any height can be estimated from

$$u(z) = \frac{u_*}{\kappa}.ln\left(\frac{z - z_d}{z_0}\right) \qquad (2)$$

where k is von Karman's constant (0.4), z is height above the ground, z_o is the roughness length and z_d is the displacement height or the effective zero wind speed height. The friction velocity (u_*) is a measure of the shearing stress that drives the flux of momentum to the Earth's surface. This logarithmic relationship describes wind-speed in the direction of airflow within a boundary layer where airflow has adjusted to the underlying surface. It is properly applied to extensive homogeneous surfaces (such as grass) under neutral atmospheric conditions and is valid under these circumstances to heights (z) above (z_d+z_o) to a limit of z* or the wake diffusion height. The zone below (z_d+z_o) may be described as the roughness sub-layer (RSL).

Urban environments are objectively rough (Table 1) causing lower mean speeds[21-23]. However, they are also heterogeneous so that the roughness sub-layer (RSL) is very deep, extending to

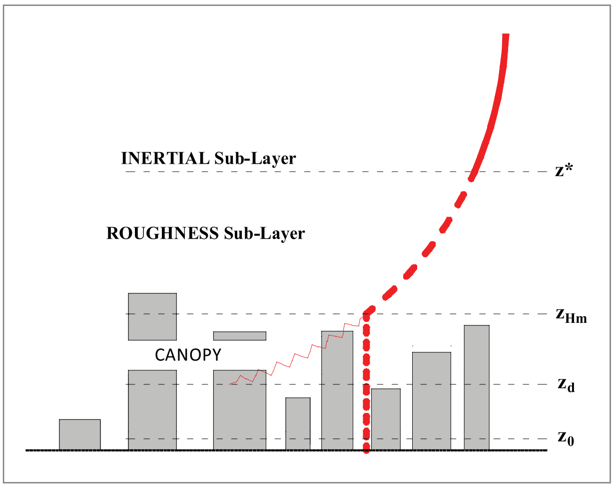

Figure 2: Air-flow modelling in terms of the logarithmic model (2). This profile performs well above z*, but within the roughness sub-layer (z*<z>zHm) the associated wind is dominated by turbulent eddies making wind classification less reliable

Table 1: Davenport classification of effective terrain roughness[25]

Roughness Class	*Roughness length (z_0)*	*Description of landscape*
Approx. Open	0.1	Moderately open country with occasional obstacles (e.g. Isolated low buildings or trees) at relative horizontal separations of at least 20 obstacle heights
Rough	0.25	Scattered obstacles (buildings) at relative distances of 8 to 12 obstacle heights for low sold objects (e.g. buildings)
Very rough	0.5	Area moderately covered by low buildings at relative separations of 3 to 7 obstacle heights and no high tress.
Skimming	1.0	Densely built-up area without much building height variation.
Chaotic	2.0	City centres with mix of low and high-rise buildings (Analysis by wind tunnel advised)

approximately twice the mean height (z^*) of the roughness elements, that is the building's height (Hz_m), that is $z^* \geq . Hz_m$. In the layer below z^*, the logarithmic profile (2) is no longer applicable. Sunderland *et al*[24] showed that for Dublin, if Eqn (2) is to be used to estimate the available wind resource in the urban area, then the height of the turbine hub should be greater than the mean obstruction height in any direction by a factor of 1.5.

Accounting for turbulence is more problematic, however. Turbulent flows can be described as those in which the fluid velocity varies significantly and irregularly, in both position and time[26]. While turbulently fluctuating flows impact directly on the design of wind turbines, they also influence the productivity of power within the turbines, particularly in areas of complex morphologies. Turbulence is considered further in Section 2.2.

2.1 Describing the wind resource

Wind speed at a site is often described statistically. Commonly employed approaches include the Weibull and Raleigh distributions. Both have been shown to give a good fit to measured wind speed data[27]. The Weibull distribution function is described in in the following equation:

$$P(u < u_i < (u + du)) = P(u > 0)\left(\frac{k}{c}\right)\left(\frac{u_i}{c}\right)^{k-1} e^{\left[-\left(\frac{u_i}{c}\right)^{k}\right]} du_i \quad (3)$$

The Weibull scaling factor, c, has the same units describing wind speed, k, represents the Weibull shape parameter, u_i is a particular wind speed and du is an incremental wind speed. $P(u < u_i < (u + du))$ is the probability that the wind speed is between u and$(u + du)$[28]. The Rayleigh distribution is a special case of the Weibull distribution in which the shape parameter, k, has a value of 2.0[28]. From (3), the Rayleigh distribution function is :

$$P(u < u_i < u + du) = P(u > 0)\left(\frac{2.u_i}{c^2}\right)^{k-1} e^{\left[-\left(\frac{u_i}{c}\right)^{k}\right]} du_i \quad (4)$$

Turbulence

When wind encounters a solid unmovable object it responds by diverting in a number of ways. Firstly, the leading edge of the object will experience an increase in pressure. Secondly, the wind stream will spread out and pass around the object and recombine after the object giving the classic teardrop shape. The recombination of wind downstream from an object is never perfect and, as a result, pressure patterns in the form of vortices are produced. One concept that is often lost is that wind is the movement of a gas and, as such, it compresses and decompresses with increasing and decreasing relative pressure. Note there is a change in direction as well as a change in wind speed as it passes an object. Also, as there is now an increase in pressure at the leading edge of the object, upstream wind is diverted around this higher pressure area, thereby creating drag and slowing down the holistic wind speed.

While this is a simple example, it does not cater for permeable objects such as trees or the complexity of multiple objects such as in an urban environment. Furthermore, increasing complex morphologies such as those contained in cities also lead to an increased surface roughness length characteristic, further contributing to the manifestation of more erratic wind speed signals.

Turbulence Intensity (*TI*) is the most common metric to explain the turbulent effect on the wind. It is generally more useful to develop descriptions of turbulence in terms of statistical properties[17]. *TI* is defined as "the ratio of wind speed standard deviation to the mean wind speed[29], determined from the same set of measured data samples of wind speed, and taken over a specified time" and should actually be considered as the standard deviation of the wind speed σ_u normalised with the mean wind speed $\bar{u}$:

$$T.I. = \frac{\sigma_u}{\bar{u}} \quad (5)$$

The complex morphology experienced in an urban environment causes a modified flow and turbulence structure in the urban atmosphere in contrast to the flow over "ideal or homogenous" surfaces. With respect to the impact on the power output of wind turbines subjected to turbulence, Cochran[30] presented a description for turbulence intensity within the lower portion of atmospheric boundary layer also based on surface roughness. His conclusions were that the (kinetic) energy available at the turbine hub height can vary by as much as 20% depending on the level of *TI* present at a site. In[31-33] the effect turbulence intensity has on the power curve of a turbine is that high *TI* exaggerates the potential output power from a turbine at moderate wind speeds (cut-in), whereas low *TI* undermines the potential output power at rated wind speed (Figure 3).

Available studies utilise measured data to provide a description of the turbulent effect and these studies are often in rural locations. However, in urban environments, unbiased high resolution wind data is difficult to acquire for wind speeds – and similarly, reliable and unbiased data for wind turbines (*vis- à-vis* localised building morphologies) in such environments is practically non-existent.

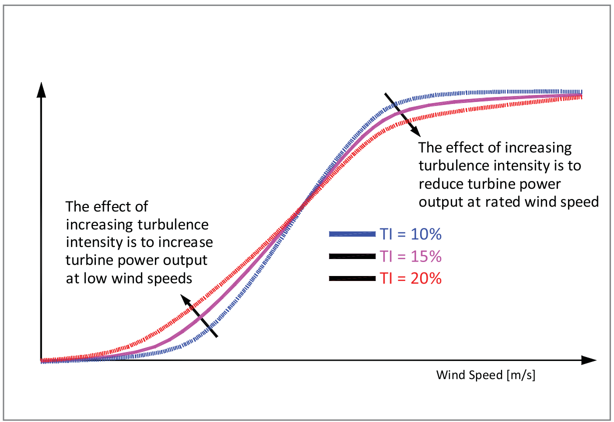

Figure 3: The effect of TI on Turbine Power Curves (interpreted from [31])

3. Power predictability using high resolution (10Hz) meteorological observations

Research carried out by Sunderland *et al*[34] considered observations made at two urban locations in Dublin, Ireland. St Pius X National (Girls) School (SUB1), located in Terenure, Dublin 6W and Dublin City Council Buildings (URB1), in Marrowbone Lane, located in Dublin 8. URB1 is located closer to the city centre than SUB1 and is therefore more urbanised with a higher associated roughness length. At both sites, high-resolution wind speed measurements were taken.

The observations were at 10Hz at an associated resolution between 0.5 and 1.0 mm/s. The analysis was based on measurements taken over a 40-day period from 4/4/2012 to 15/5/2012. Consistent with the industry standard[29], a 10-minute sampling period was employed on a moving window basis with each window consisting of 6000 samples (10 minutes at 10Hz). Two models were developed to quantify the affect of turbulence on the productivity of a wind turbine in an urban environment*. The first approach was an adaptation of a model originally derived to quantify the degradation of power performance of a wind turbine using the Gaussian probability distribution (*Albers* approximation) to simulate turbulence (and more specifically, turbulence intensity (*TI*))[35]. The second approach used the *Weibull Distribution*, a widely-accepted means to probabilistically describe wind speed.

The advantage of the high-resolution observations in testing the models is the ability to interrogate the 6000 wind speed datums within the 10-minute interval. This facilitates inter comparison of the models against the power if it could be recorded at such high resolution and also against the standard industry approach that quantifies the turbine power output on the basis of the 10-minute mean wind speed. Figure 4 illustrates a comparison of the performance of the models over the 40-day period.

Each observation window considers three power measurements – the *Albers approximation* P_{norm}, the *Weibull approximation*, P_{weib}, and the average power over the window, P_{mean}, which is calculated

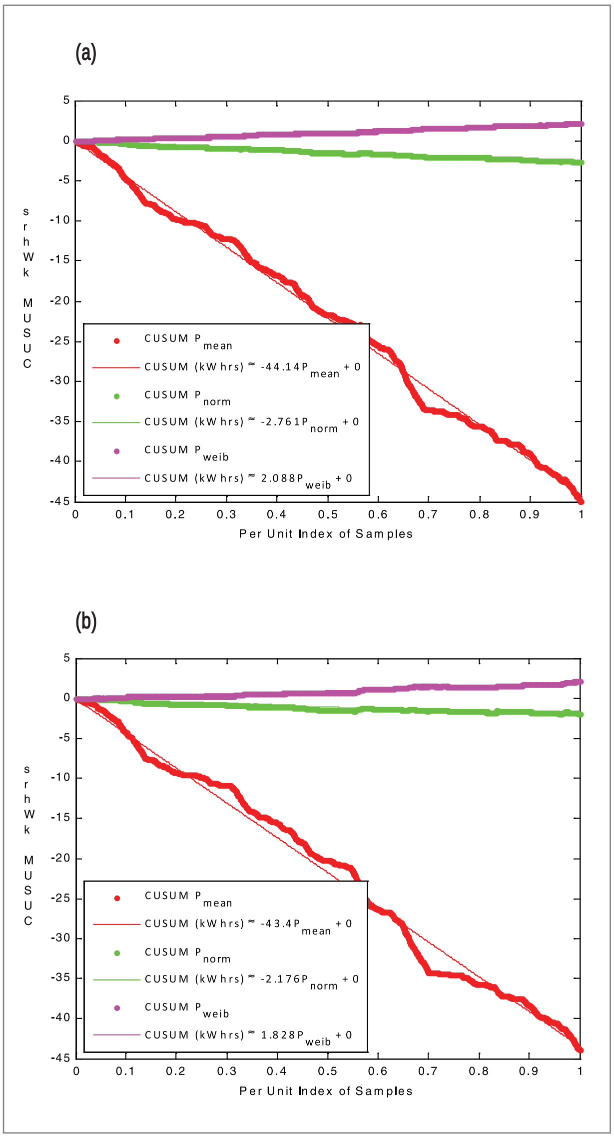

Figure 4: The cumulative error for each of the calculated power models (*Pmean, Pnorm* and *Pweib*) for both sites (URB1 (a) and SUB1 (b)). Putting this in context, both the Albers or Weibull turbulence models for both sites have over 90% of its error within 50W of the *Pabs* at both sites

by considering the turbine characteristic with respect to the mean speed over the observation window. P_{mean}, is the industry norm for data logging of power output from wind turbines. Each of these calculations is benchmarked against the *absolute power*, P_{abs}, which is the average of individualised (6000) calculations. Figure 4 actually presents a cumulative sum of differences that occur throughout the full set of 40 days of data; Figure 4(a) illustrates this trend analysis for URB1; and Figure 4(b) illustrates similar for SUB1. It is clearly evident that for both sites, P_{weib} and P_{norm} are virtually horizontal, with only a slight over-prediction derived using P_{weib} and under-prediction using P_{norm} cumulatively derived over the 40 days of observations. This strongly implies that both models are consistent with the P_{abs} measurements and are accurate with respect to representing practically the effect of turbulence on the wind turbine.

* *The wind energy system considered was a Skystream 3.7, 2.4kW turbine*

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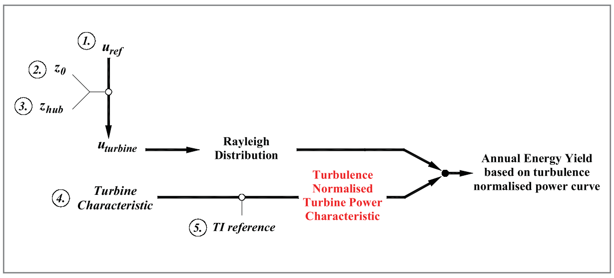

Figure 5: Flow chart illustrating how SWEET incorporates varying surface roughness (z_0) and turbulence intensity (*TI*) (this SWEET tool is available FREE at http://arrow.dit.ie/sdar/)

4. Wind energy prediction: a refined approach (SWEET)

One of the aims of this paper was to describe an accessible tool (developed in MS EXCEL) that can facilitate an estimate of the wind energy based on the land surface and likely prevalence of turbulence. The Small Wind Energy Estimation Tool (SWEET) was therefore developed in this regard and is available at http://arrow.dit.ie/sdar/. More specifically, *SWEET* provides the user a means to approximate the annual electrical energy yield from a generic wind turbine based on the following input parameters:

1. A reference wind speed (for example one such wind resource mapping repository is available from the *Sustainable Energy Authority of Ireland* (SEAI) at http://maps.seai.ie/wind/#)
2. A value describing the surface roughness. The tool employs a scaling version of the log law (6)

$$v_{hub} = v_{ref} \frac{ln\left(z_{hub}/z_0\right)}{ln\left(z_{ref}/z_0\right)} \qquad (6)$$

   where v_{hub} is the wind speed at the hub height (z_{hub}) and v_{hub} and (z_{hub}) represent the wind speed and height of the reference resource respectively
3. A hub height for the wind turbine
4. The turbine characteristic contained within the tool is generic. Users can overwrite the power curve data with alternatives if they choose
5. A turbulence intensity value based on 0.1<*TI*<0.7, with a *TI* of 0.7

Figure 5 presents a flow chart to illustrate how the tool is used.

SWEET uses the wind speed reference acquired from a wind speed reference such as the one developed by SEAI and extrapolates this wind speed logarithmically to the turbine hub height as specified by the user in terms of the surface roughness, again specified by the user. The turbine power characteristic (either the generic curve contained within the tool or an alternative) is turbulence modified. The normalisation is based on a Gaussian distribution approximation developed by Sunderland *et al*[34]. Essentially, the turbine power at the extrapolated wind speed is modified in terms of a turbulence model which is itself based on a

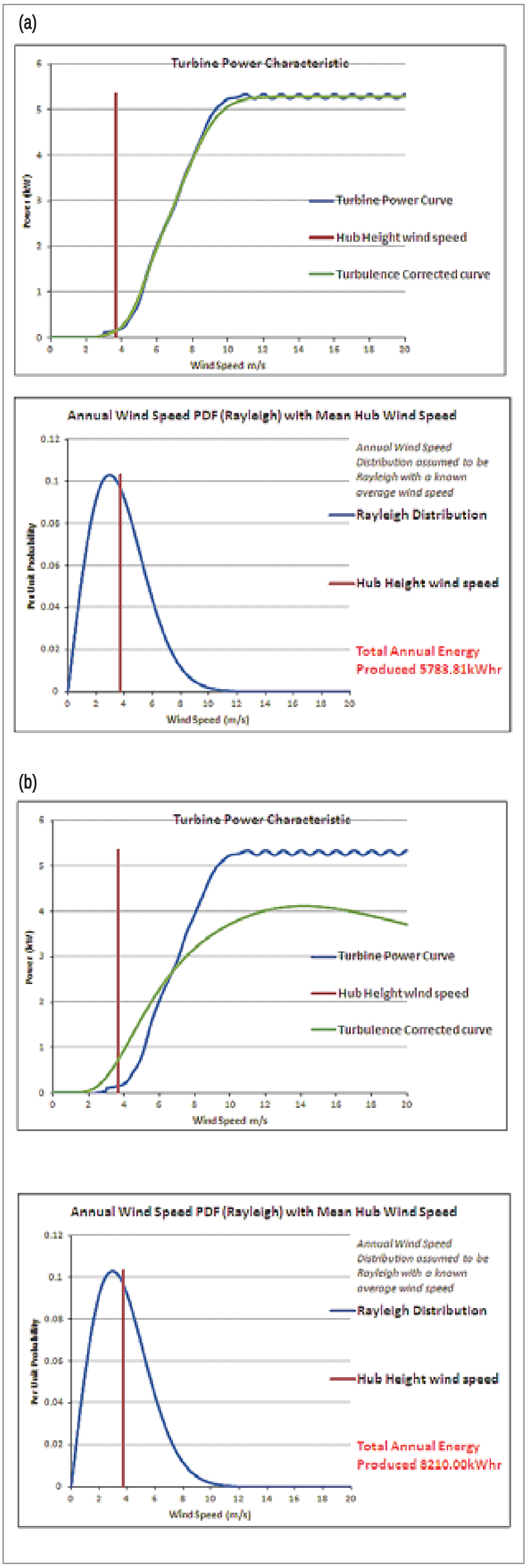

Figure 6: Screen shots of *SWEET* in terms of varying *TI*

Gaussian distribution with a mean wind speed of the extrapolated wind reference and a standard deviation acquired through (3).

Looking at screen shots of the tool outputs (http://arrow.dit.ie/sdar/), Figure 6(a) illustrates the yield calculated when the reference wind speed is 5m/s and *TI* is 10% (for a hub height of 15m and a very rough surface (Table 1) roughness characteristic (z_0=0.5)). Figure 6(b) then illustrates how the resource is affected if the turbulence intensity is increased to 60%. The yield appears to increase by 42%! This is one of the limitations of the turbulence modelling using a Gaussian distribution. The turbine power curve is *skewed* by the higher turbulence intensity exaggerating the potential output power from the turbine at moderate wind speed (highlighted) and, as a consequence derives a higher yield.

On the other hand, if the reference wind speed is increased to 10m/s for the same input considerations (z_0, z_{hub}), the energy yield will decrease by almost 13% when the *TI* is 60% when compared to the yield derived with a *TI* of 10%.

4.1 Conclusions and further work

This paper describes the complications associated with wind energy estimation, particularly in the urban environment. It is evident that the associated complexities within an urban context pose many challenges to micro wind energy installation designers and those wishing to use this form of renewable energy. In particular, what turbulence is and more importantly how it affects micro wind energy systems are significant issues. In consideration of a model that employs Gaussian statistics in[34] a refinement that can be accessed through a readily-available platform (Excel) was devised, namely *SWEET*. While not affording the depth of accuracy available when 10Hz data is available, this tool can serve to facilitate an estimation of wind energy yield expected at a site, as well as affording insight for engineers within the built environment to the challenges involved in optimally locating such turbines.

However, there are a number of caveats associated with *SWEET* (as described on the first page of the tool):

– Turbulence intensity is indicative for all associated site wind speeds. In this regard, the approach is predicated on the wind speed sampling being described accurately by a Gaussian probability distribution;

– The wind speeds are longitudinal in nature, i.e., always flowing directly into the turbine hub and the climate is neutrally buoyant;

– The mechanical inertia of the turbine is not taken into consideration. The reaction/yawing of a turbine in fluctuating wind speed will detract from its energy producing capability;

– The input turbine characteristic employed is indicative of a 0% turbulent environment.

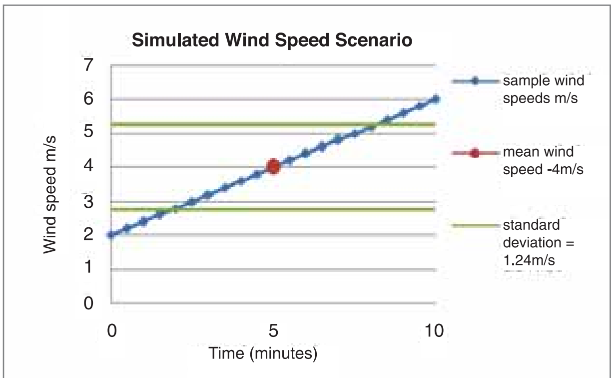

Figure 7: Wind speed trending within an observation window

A further limitation of the approach is in the consideration of *TI* as the metric to define turbulence, particularly in highly-turbulent environments or when the wind speed approaches 0m/s. Firstly, *TI* is based on Gaussian markers and the signal may or may not represent a Gaussian form. There is also potentially a problem with trending within the wind speed window being considered as turbulence when in fact it could be a gradual change in wind speed, something acknowledged by the industry standard[29], which employs the *Normal Turbulence model* (a precursor to the Gaussian approximated described here).

Finally, and with respect to *SWEET*, both the surface roughness parameter and *TI* reference are entered separately. Mertens[36] proposes that *TI* can be linked to the surface roughness parameter. Such a linkage was considered and, as suggested in[34] is an area warranting further consideration.

As can be demonstrated in the model there are several other factors that could be considered as a means of improving the estimation capability. Firstly, *SWEET* has no means to consider the most predominant wind direction for turbulence manifestation and is something that could possibly be included on a turbulence rose. Secondly, the inability of any PDF (Probability Distribution Function) markers to accurately regenerate to a time series is an issue when trying to establish the effect of inertia and its resultant time constant on the system. A novel model, the *Turbulent Fourier Dimension* (T_{Df}) that measures turbulence and maintains the ability to interchange between the time domain and frequency domain is currently being investigated.

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